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Gluon Fragmentation into Glueballs and Hybrid Mesons [1]

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Abstract

The constituent nature of candidate gluonic mesons can be studied by comparing their production in quark and gluon jets. The production rate for such mesons depends on the colour confinement processes at the end of the perturbative evolution. Whereas we expect enhanced production of hybrids in the fragmentation region of a gluon jet, the rate for glueballs depends on the relative importance of colour triplet and colour octet neutralization. These neutralization processes can be studied independently in events with large rapidity gaps. If octet processes turn out important the recently suggested lightest $J^{PC} = 0^{++}$ glueball with mass around 1000 MeV should become visible already in the spectrum of the leading charged particle pairs.

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1 Introduction

A characteristic prediction of QCD in the non-perturbative sector concerns the existence of mesons with gluons as valence constituents, either purely gluonic mesons, “glueballs”, or “hybrids”, the bound states of quark, antiquark and gluon.

The search for glueballs is an important issue since the early days of QCD [1] but their very existence has not been definitely established until today. Whereas there is general agreement that the lightest glueball should have quantum numbers $J^{PC} = 0^{++}$ its mass remains controversial. Moreover, as $q\overline{q}$ mesons exist with the same quantum numbers the identification is difficult, in particular, as there could be mixing between the different states as well.

The important way to distinguish between the possibilities is the study of production rates and decay branching ratios which are expected to be sensitive to the constituent structure. Glueballs are expected to be produced preferentially in a gluon rich environment such as $J/\psi \to \gamma + X$, central production in hadron hadron collisions by double Pomeron exchange and $p\overline{p}$ annihilation into mesons near threshold. On the other hand, glueball production should be suppressed in $\gamma\gamma$ collisions (see [2] for survey). All these reactions have been explored with increasing accuracy in the past.

Here we want to discuss another pair of reactions where glueball or hybrid production could be enhanced or suppressed, respectively. In the fragmentation region of the quark jet the usual $q\overline{q}$ hadrons which carry the initial quark as valence quark are enhanced, gluonic mesons are expected to be suppressed. In analogy, one might expect gluonic mesons to be enhanced in the fragmentation region of gluon jets and $q\overline{q}$ states to be suppressed. Correspondingly, one may study the relevant particle systems ($\pi\pi,\ K\overline{K},\ 4\pi\ldots$) either at large momentum fraction (Feynman x), or with some advantages, in the head of the jet beyond a large rapidity gap (length Δy). Of advantage are the similar kinematic conditions for both kinds of jets and often the possibility of a measurement in the same experiment. The own identity of gluon jets produced in hard collisions has been established in various details according to the expectations from perturbative QCD calculations (for review, see [3]). There are plenty of gluon jets in the $e^+e^- \to q\overline{q}g$ final states and in hard pp collisions which makes this type of studies promising.

Experimental studies along this line have not been carried out so far although there is some history to the idea to look for gluonic mesons in gluon jets. Peterson and Walsh [4] suggested a non-perturbative model with a leading isoscalar cluster in the gluon jet which could be composed of ordinary $q\overline{q}$ mesons like $\eta, \eta', \omega, \phi$ or glueballs. An enhanced production of η' in gluon jets because of its intrinsic gg component has been suggested by Fritzsch [5]

in the explanation of the large decay rate of B into η'. More recently, Roy and Sridhar [6,7] suggested the search for glueballs in gluon jets at large x and considered a model with the $g \to gb$ fragmentation being similar to $q \to \pi$ fragmentation.

Whereas an earlier study at LEP [8] presented evidence for an enhanced η production in gluon jets at large x the more recent studies of η, η' mesons [9,10] did not indicate any enhanced production of isoscalar mesons in gluon jets. No study has been published yet for glueball or hybrid candidates.

Whether the suggested systematics is realized in nature depends on the (nonperturbative) colour neutralization mechanism and could be quite different for ordinary $q\overline{q}$ mesons, hybrids and glueballs. We distinguish the colour triplet and colour octet neutralization and suggest studies which should reveal the relative importance of both mechanisms independently of the existence of glueballs. In any case, we expect the enhanced production of hybrids in gluon jets – if they really exist (see also [11]).

2 Status of glueballs and hybrids

Lattice calculations in quenched approximation (without sea quarks) put the lightest glueball with quantum numbers $J^{PC} = 0^{++}$ near a mass of 1600 MeV [12,13] (for a review, see [14]). First results from unquenched calculations [15] are not yet conclusive but may indicate a decrease of the glueball mass with decreasing quark mass.

On the other hand, within the QCD sum rule approach, a lighter gluonic component in the 0^{++} spectrum is required near 1000 MeV [16] (earlier results in [17]). Also the early calculations in the MIT bag model [18] prefer the low mass glueball around 1000 MeV.

In a recent phenomenological analysis [19] it has been proposed that the lightest 0^{++} glueball should be identified with the very broad state

$$gb(0^{++}): \qquad M \ = \ 1000 \text{ MeV}, \qquad \Gamma \ = \ 500 \ - \ 1000 \text{ MeV} \tag{1}$$

which corresponds to both states $f_0(400-1200)$ and $f_0(1370)$ listed in the particle data table [20]. Whereas in some experimental mass spectra there is a separate peak near 1370 MeV the phase shift analyses of elastic and inelastic $\pi\pi$ scattering do not indicate the phase movement corresponding to an ordinary Breit Wigner resonance centered at this mass value. Rather – after removal of the narrow $f_0(980)$ – the $\pi\pi$ elastic scattering phase shifts below 1500 MeV are slowly rising and pass through 90^o near 1000 MeV; there is no indication of a second resonance – neither in the elastic [21] nor in the inelastic channels [19].

Recent data on central production of particle pairs by the WA102 and GAMS collaborations [22,23] show again peaks in the mass spectra near $f_0(1370)$; the measured angular distribution moments should now allow a judgement in favour of the Breit-Wigner resonance phase movement or against it from the interference with $f_2(1270)$; the same applies also to peripheral $\pi^0\pi^0$ production in πp production by the E852 collaboration [24]. Relative phases may also be obtained in the 4π final states measured by WA102 [25]. Such analyses have the potential to further clarify whether $f_0(1370)$ is a reasonably narrow ($\Gamma \sim 200 - 300$ MeV) Breit-Wigner resonance or – as we suggested [19] – a component of a yet broader object.

The broad state $gb(1000)$ in (1) is found consistent with most expectations for production and decay of a glueball and is therefore a respectable candidate. The main decay mode is $\pi\pi$, but also $K\overline{K}$ and $\eta\eta$ above the respective thresholds and possibly $\pi\pi e^+e^-$ [26]. The identification of $f_0(1500)$ as lightest glueball is not supported by the finding of opposite signs for the decay amplitude into $K\overline{K}$ and $\eta\eta$ [19].

There is even less experimental information about 0^{-+} and 2^{++} glueballs. Possible candidates according to the analysis of ref. [19] are $\eta(1440)$ and $f_J(1710)$ with $J = 2$.

In the sector of hybrid mesons the spin-exotic state 1^{-+} is of particular interest. Lattice results yield mass values around 1900 MeV for this hybrid composed of light quarks and gluon in quenched approximation and also in the first attempt including sea quarks [27,28,29,14].

There is experimental evidence for resonances with exotic 1^{-+} quantum numbers in the $\eta\pi$ system at masses around 1400 and 1600 MeV (for a recent summary, see Chung [30]). This result is lower than the lattice expectation by around 500 MeV. This discrepency could be due to an incomplete calculation or the observed states are not hybrid but other exotic states, for example $q\bar{q}q\bar{q}$ states.

3 Hadron production and colour neutralization

An energetic quark or gluon emerging from a hard collision process will generate a parton cascade by subsequent gluon bremsstrahlung and quark pair production. The extension of such a cascade for a 100 GeV jet in space can be rather large and exceed 100 f (see, for example [31,32]). The formation of colour singlet systems should proceed during the evolution whenever the separation of colour charges exceeds the confinement length $R_c \sim 1$f. Two types

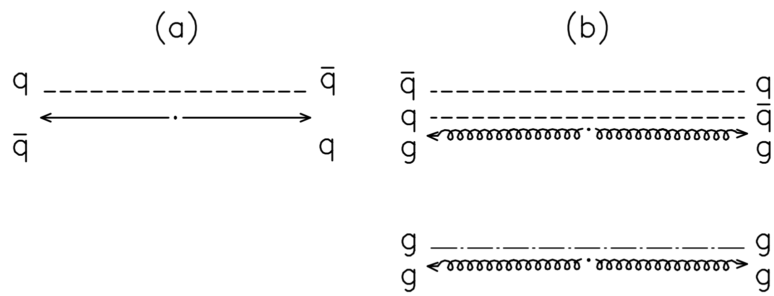

Figure 1: The colour neutralization (a) of an initial $q\overline{q}$ pair by $\overline{q}q$ and (b) of an initial gg pair by either double colour triplet $q\overline{q}$ or by colour octet gg

of neutralization processes are possible (see Fig. 1).

1. Colour triplet neutralization.

Consider the production of a massive $q\overline{q}$ pair in a colour singlet state in its restframe corresponding to separating colour triplet charges (possibly accompanied by secondary partons from bremsstrahlung). The colour field between the primary quarks can be neutralized eventually by the (nonperturbative) production of a soft quark antiquark pair. This process of triplet neutralization may repeat itself for the various branchings inside the quark gluon cascade until the total energy is carried by $q\overline{q}$ hadrons. Also possible is the formation of hybrid mesons from the gluons at the end of the perturbative cascade and the soft $q\overline{q}$. An example for a quantitative description of soft nonperturbative $q\overline{q}$ production is given by the chromoelectric flux tube model [33] which considers pair production in a static field. A systematic treatment for relativistic particles connecting to perturbation theory has not yet been achieved.

2. Colour octet neutralization.

In case of a primary colour singlet gg pair the field between the separating colour octet charges can be neutralized at the confinement distance either by the production of a gluon pair or by the subsequent production of two quark pairs. Only the mechanism with gluon pair production could yield pure gluonic bound states at the end.

We introduce the relative probability of triplet and octet neutralization by a phenomenological parameter

$$R_3 \;=\; P_3/P_8. \tag{2}$$

In the flux tube model of ref. [33] the octet process was considered negligible assuming a large effective gluon mass $>$ 1 GeV in expectation of a heavy glueball. We consider here the possibility of a light glueball and also of a non-negligable soft gg production rate.

It is not obvious to what extent the two types of neutralization mechanisms are realized in a particular process. Common collision processes at particle accelerators are initiated by quarks either as constituents of external hadrons or after production through electromagnetic or weak gauge bosons. A successive triplet neutralization by quark pairs is then always possible even in a gluon dominated final state. The octet neutralization could be an overall rare process enhanced for particular kinematic configurations.

Here we suggest such a configuration: consider the production of a hard gluon which travels without gluon radiation for a while forming a jet with a large rapidity gap empty of hadrons. The probability for such events decreases exponentially with the rapidity gap according to the Sudakov formfactor [32]. In this case the hard isolated gluon builds up an octet field to the remaining partons which is not distorted by multiple gluon emissions and related colour neutralization processes of smaller rapidity range, so the gg octet mechanism may be enhanced and will become clearly visible if it exists.

The experimental test can be carried out independently of the existence of glueballs. In case of gg neutralization the total charge of the head particles beyond the gap should be $Q = 0$; on the other hand, the charge distribution in case of double triplet neutralization should have a component with charges $Q = \pm 1$, a situation which is also met for an equal mixture of quark and antiquark jets with a gap. Therefore, if the colour octet mechanism exists, the charge distribution for the gluon gap events should be a mixture of both components according to the probability R_3 in (2).

In this test the gap Δy should be large enough so that the leading charges have approached a limiting distribution; only the charges which correspond to the combination of the leading parton and the soft neutralizing parton (or partons) are present. In this limit multiple exchanges through the gap and leading charges $|Q| \geq 2$ should be absent.

If the enhanced neutral component from octet neutralization is not observed we would not expect a preferred source of glueballs in gluon jets either. In this case glueballs would be produced through their mixing with quarkonium states in any collision process and not preferentially through their valence glue component.

4 Limiting charge distribution beyond the gap

For illustration we give an estimate of the limiting charge distribution for sufficiently large Δy in the head of the jet beyond the gap for the case of triplet neutralization. We assume that the charge is determined in the quark jet by the charge of the leading quark and an average soft antiquark and in

case of gluon jet by the average charge of the soft quarks and antiquarks. In our estimate we assume that soft u, d, s quarks are produced with relative probabilities γ, γ, γ_s and we take $\gamma = 0.4, \gamma_s = 1-2\gamma = 0.2$ as in ref. [34] in the example (i.e. the production ratio $s/u = 0.5$). More generally, γ could depend on the energy scale of the separating partons and we compare also with the extreme cases $\gamma = 1/2$ $(s/u = 0)$ and $\gamma = 1/3$ $(s/u = 1)$.

The charge distribution in the head of the gluon jet is then given by

$$p_g(Q) \;=\; P_3 p_3^g(Q) + P_8 p_8^g(Q) \tag{3}$$

where the charge distributions for triplet and octet neutralization $p_3^g(Q)$ and $p_8^g(Q)$ are given in Table 1. As seen from the table, the probabilities vary within 10% for the different assumptions on the strange quark ratio s/u. From the measurement of the charge distribution (3) one can determine the ratio R_3 in (2), given the parameter γ.

The corresponding analysis can be done as well in quark jets with a gap to check the overall picture and study the parameter γ. The charge distribution in the head of the jet for different quarks and the quark-antiquark average relevant to e^+e^- events is given in Table 2. For a superposition of different quark (anti-quark) jets with probabilities $\hat{P}_q$ the charge distribution is given by

$$\hat{P}_{<q>}(Q) \;=\; \sum_q \hat{P}_q \; p_3^q(Q). \tag{4}$$

There are some differences between the gluon jet with triplet neutralization and the $q\overline{q}$ average jet, but both are clearly separated from the octet case which can therefore easily be identified with this method.

5 Fragmentation Region of Gluon and Quark Jets

The inclusive spectra of hadrons and other observables are well described by the corresponding quantities at the parton level provided the perturbative evolution is continued down to small values of the k_T cutoff in the cascade $Q_0 \sim \Lambda_{QCD}$ (this phenomenological approach is called "local parton hadron duality", for reviews, see [31,3]). In this picture the x-distribution of hadrons in the gluon jet is steeper than in the quark jet because of the stronger semi-soft gluon radiation in the gluon jet.

As to the fragmentation region of the quark jet it is by now well established that the hadrons which carry the primary quark as a valence quark dominate at

Table 1: Leading charge distribution $p_3^g(Q)$ and $p_8^g(Q)$ in a gluon jet in case of triplet neutralization by soft u, d, s quarks and anti-quarks for different values of the $s/u \equiv \gamma_s/\gamma$ ratio and octet neutralization by gluons.

	triplet $p_3^g(Q)$				octet $p_8^g(Q)$
	$s/u = (1-2\gamma)/\gamma$	$s/u = 0.5$	$s/u = 0$	$s/u = 1.0$	g
$p_c^g(Q=0)$	$1-2\gamma+2\gamma^2$	0.52	0.5	0.56	1
$p_c^g(Q=1)$	$\gamma(1-\gamma)$	0.24	0.25	0.22	0
$p_c^g(Q=-1)$	$\gamma(1-\gamma)$	0.24	0.25	0.22	0

Table 2: Leading charge distribution $p_3^g(Q)$ in quark jets; numerical values for $s/u = 0.5$.

	u or c		$(u+\overline{u})/2$	d or b		$(d+\overline{d})/2$	s		$(s+\overline{s})/2$
$P_3(Q=0)$	γ	0.4	0.4	γ	0.4	0.4	$1-\gamma$	0.6	0.6
$P_3(Q=1)$	$1-\gamma$	0.6	0.3	0	0.0	0.3	0	0.0	0.2
$P_3(Q=-1)$	0	0	0.3	$1-\gamma$	0.6	0.3	γ	0.4	0.2

large momentum fraction x as expected in the parton model [36]. The leading hadron follows the distribution of the primary quark if it is color-neutralized by a soft anti-quark.

In the gluon jet, in case of triplet neutralization, the leading particles are the hadrons formed by the primary gluon and the soft $q\overline{q}$ pairs. If there are hybrid mesons they may be formed in the fast colour singlet $q\overline{q}g$ system, alternatively, the fast hadrons are ordinary $q\overline{q}$ mesons formed at the end of the parton cascade after having absorbed all gluon energy. If the octet mechanism is at work the leading gluon may also form a glueball. On the other hand, in the quark jet neither the hybrid nor the glueball will be leading if – as we assume – the leading quark is only neutralized in colour by a soft antiquark. These properties are summarized in Table 3.

The constituent nature of a particular particle or resonance according to Table 3 can best be studied by comparing its production rate in the frag-

Table 3: Production of leading hadrons in the jet

	neutralization	$\overline{q}q$	hybrid	glueball
quark jet	triplet	yes	no	no
gluon jet	triplet	yes	yes	no
	octet	no	no	yes

mentation region of quark and gluon jets. One possibility is the study of the respective mass spectra at large x (see also [6]); there may be considerable non-resonant background. Another possibility is the study of particles beyond the rapidity gap. For large gaps when the limiting charge distribution is reached the background should be small. As argued above the rapidity cut may enhance the possibility for the octet mechanism.

The comparison between quark and gluon jet is best carried out for similar kinematic configuration: the same length δy for the head of the jet beyond the gap in a frame with the nearest jets in angle $\geq 90^o$.

For the gluon jet in $e^+e^- \to 3$ jets such a preferred frame is reached after transforming first into the restframe of $q\overline{q}$ and then boosting along the $q\overline{q}$ direction until the g jet is perpendicular (see Fig. 2).

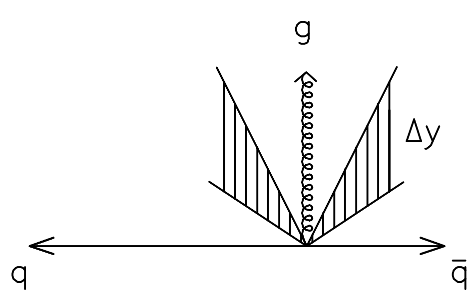

Figure 2: Convenient frame to analyse gluon jets with a rapidity gap Δy in three jet events in e^+e^- annihilation.

In order to correct for the different inclusive parton distributions in quark and gluon jets and also in case of different available phase space it is best to normalize the rates to a well known $q\overline{q}$ hadron h_{norm} $(\rho,\ f_2\dots)$ of comparable

mass. Along this way we define the gluon factor F_g for a hadron h

$$F_g(h/h_{norm}) \;=\; \frac{\sigma(g \to h)/\sigma(g \to h_{norm})}{\sigma(q \to h)/\sigma(q \to h_{norm})}. \tag{5}$$

Apparently, for a $q\overline{q}$ hadron the gluon factor $F_g \approx 1$ and for a gluonic meson $F_g \gg 1$.[2]

According to our hypothesis about $gb(1000)$ as being the lightest binary glueball an effect $F_g > 1$ should be seen for the mass spectrum of $\pi^+\pi^-$ or $\pi^0\pi^0$ around and below 1 GeV, i.e. in the simplest case already for a neutral pair of charged particles. It may be compared with $\rho(770)$, $f_2(1270)$. Other enigmatic states like the $f_0(980)$ can be tested for their gluonic components as well. Heavier glueball candidates like $f_0(1500)$ and $f_J(1710)$ may be studied through their $K\overline{K}$ decay modes. Also the mass spectrum of all particles with total charge $Q = 0$ in the head of the gluon jet beyond the rapidity gap would be an interesting possibility for inclusive glueball hunting.

6 Conclusions

The limiting charge distribution in the leading cluster of quark and gluon jets with sufficiently large rapidity gap should reveal the relative importance of the octet neutralization mechanism. The comparison of such events in quark and gluon jets could then provide some clues about the constituent nature of candidate gluonic mesons with low background. Inclusive particle spectra did not prove any unusual behaviour in both kinds of jets so far, but particle correlations could do. Interesting tests are already possible with charged particle pairs.

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